

# Pulsation Modes of Mira Variables Examined through IR Interferometry

M.J. Creech-Eakman<sup>1,\*</sup>, R. R. Thompson<sup>1,2</sup>, G. T. van Belle<sup>1</sup>

<sup>1</sup> Jet Propulsion Laboratory, Caltech

<sup>2</sup>University of Wyoming;

\*mce@huey.jpl.nasa.gov

## ABSTRACT

We have undertaken a program with the Palomar Testbed Interferometer (PTI) to measure the angular size variations, with respect to pulsational phase, of a group of about 20 mainly O-rich Mira variables. While previous groups have attempted to measure angular size with phase (van Belle et al. 1996, 1997; Tej et al. 1999) these are the first dedicated, spatially-resolved K band observations designed to detect size variations in a large sample of Miras at regular intervals over their pulsation periods. Our first goal has been the unambiguous detection of the mira pulsational cycle with phase, already shown in previous work to be as much as 35% of the radial size over the course of a pulsational period (van Belle et al. 1996; Burns et al. 1997; Tuthill et al. 1995; Perrin et al. 1999). We will ultimately use these data, along with the best estimates of stellar distance and effective temperatures for these sources, to determine the mode of pulsation. There has long been a debate as to whether Mira variables pulsate in their fundamental or first-overtone mode (Barthes 1999; Feast 1998; Wood & Sebo 1996). Determination of the pulsation behavior of Mira variables may eventually render them suitable as standard candles for distance determination.

## 1. Introduction

PTI is a long-baseline near-infrared interferometer located at Palomar Observatory (Colavita 1999). During the 1999 observing season, we have had a dedicated program to study the pulsational characteristics of a group of 20 mostly oxygen-rich mira variable stars with two main objectives. First, we are trying to determine whether we can routinely detect changes in size due to pulsation of the mira. Second, we have the goal of ascertaining the pulsational mode of these miras - a long-term controversy in the field.

To carry out these two goals, we observe the miras approximately every 10 days (about 3% of a typical period) in K-band with respect to two, usually unresolved, calibration stars for about 1.5 hours. This observation schedule is continued for each star for approximately three months centered around visual maximum of the mira, and dependent upon coordinates of the star and LST. For those sources found to be small enough ( $\leq 4.5$  mas) to observe, approximately 50% of the observations undertaken are successful. Unsuccessful observations can typically be attributed to either bad weather conditions, or trouble acquiring these miras at R band due to their faintness.

Here we describe the calibration and reduction method and our analysis of 10 miras from our sample for which there is adequate phase coverage (see Table 1). In section 2 we describe the instrument, measurements and analysis methods. In section 3 we show the phase coverage for our shortest period mira, R Vir, where pulsation has been unambiguously detected. Discussion of the pulsation mode and what is implied by our results is in section 4. And in the final section we draw conclusions based upon this work.

## 2. Instrument, Measurements and Analysis Method

The interferometric observable used for these measurements is the fringe *visibility* (squared) of a brightness distribution on the sky. Normalized in the interval [0:1], a uniform disk model for a single star exhibits visibility modulus given by:

$$V = \frac{2 J_1(\pi B \theta / \lambda)}{\pi B \theta / \lambda} \quad (1)$$

where  $B$  is the projected baseline vector magnitude,  $\theta$  is the angular diameter of the star, and  $\lambda$  is the observation wavelength.

Estimation of the angular diameter of an individual star is accomplished by calibrating the instrumental visibility on each night using nearly unresolved ( $\leq 0.6$  mas) stars. In order to do this, a size estimate is made for the calibration stars based on their bolometric luminosity and spectral type, using archival optical and infrared data from Simbad and the Catalog of Infrared Observations. See Figure 1 for a sample plot of one of the calibration stars used in this program, HD128167, illustrating this technique. The software to perform this search and estimate was written and supplied to the PTI collaboration by A. F. Boden.

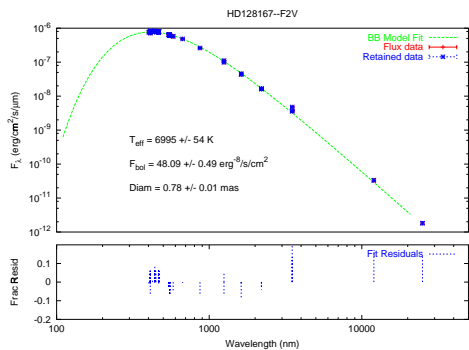


Fig. 1 Estimate of bolometric flux, effective temperature and angular diameter of HD128167 (a calibration star) based on archival optical and infrared data. The program to perform this search and estimation was written and supplied to the PTI collaboration by A. F. Boden.

Using at least two calibration stars, taken within about one hour and 10-15 degrees of the target star, a system visibility is estimated and the visibility of the target star calibrated. The calibration stars' estimated angular diameters are iterated upon until a solution consistent with their spectral types and estimated Hipparcos distances are converged to, or the observations are discarded for that night. Corrections are applied to the data for fringe jitter (underestimation of visibility due to imperfect tracking of the fringe). All estimates of angular size in this paper assume a uniform disk model. See Figure 2 for a sample of calibrated V2 data on mira variable S Lac and its two calibrators.

Detection of pulsation by measuring changes in angular size with respect to phase of the mira variable has been accomplished by a handful of groups (van Belle et al. 1996; Burns et al. 1997; Tuthill et al. 1995; Perrin et al. 1999). In some of these experiments, up to a 35% change in angular diameter has been seen for these stars. Assuming a typical mira of  $200 R_{\odot}$  at a distance of 500 pc, we would expect an ideal calibrated visibility for an interferometer such as PTI (K band, 100 m projected baseline) of 0.138. A 10% change in size to  $220 R_{\odot}$  would drop the visibility to 0.080 (while a 10% change to  $180 R_{\odot}$  would raise the visibility to 0.214). Changes of the visibility at this magnitude should be easily recognizable, assuming careful calibration.

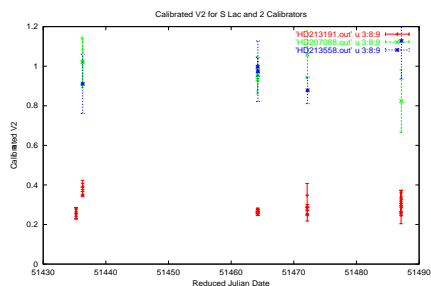


Fig. 2 Calibrated V2 measurements on S Lac and its two calibrators for the 1999 observing season.

Only one star in our sample, R Vir, has a short enough period to allow for adequate phase coverage during the 1999 PTI observing season. We see excursions in the angular diameter of 0.646 mas (from 3.527 to 2.881) over its 145.51 day period. Assuming a distance (see below) of approximately 540 pc, this suggests the radial size changes from  $199 R_{\odot}$  near visual maximum, to  $167 R_{\odot}$  near visual minimum - a change of 17% over the average size. See Figure 3 for the radial size with respect to phase. We have also plotted the visual magnitude from AFOEV with this data to help the eye identify the phase minimum. While we see changes in size in nearly all the miras in our sample, these changes are, as yet, too small to make definitive statements mainly because the phase coverage has been inadequate because only a few months of the observing season were dedicated to observations of each star.

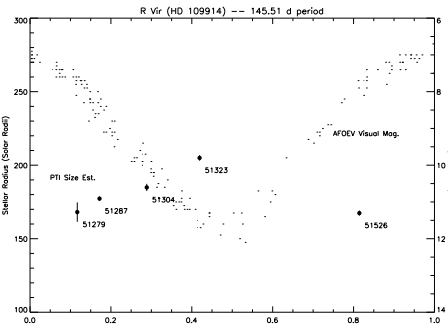


Fig. 3 We plot estimated radius (in  $R_{\odot}$ ) of R Vir with respect to visual phase of the mira. We have superimposed the visual magnitude during the same phase cycle with this data to guide the eye as to the positions of visual max/min. This data was obtained from the AFOEV database.

We further anticipate that continued observations through the 2000 observing season will allow us not only to determine the radial excursions of these miras with phase, but also, with adequate coverage, to identify the phase lag between radial size and visual brightening. This lag, assumed to be caused by the effects of acoustic shocks (which drive the mira pulsation cycle) on the outer layers of the mira atmosphere and surroundings, and overshooting of the pulsation during compensation to return the star to hydrostatic equilibrium, has been demonstrated at other wavelengths by several groups (c. f. Lockwood & Wing, 1971, Creech-Eakman, 1997).

Table 2: Distances to Miras

Star	Hip (pc)	Hip (near) (pc)	Hip (far) (pc)	van Leeuwen (pc)	A & M (pc)
R Vir	714	356	...	538	540
R Boo	...	...	...	749	460
V Crb	1960	694	...	692	...
R Tri	398	238	1220	519	300
S Lac	667	317	...	928	...
TU And	...	...	...	905	...
U Cas	...	...	...	994	...
R Gem	...	...	...	986	...
V Cmi	...	...	...	944	...
R Psc	...	...	...	1001	680

Table 1: Stars in Sample

Star	Spec. Type	Period (d)	Epoch (Red. JD)	Ang. Size (mas)	Num. Obs.
R Vir	M4.5IIIe	145.51	51262	$3.106 \pm 0.131$	5
R Boo	M4e	223.41	51019	$3.447 \pm 0.103$	5
V Crb	Ce	357.82	50961	$3.997 \pm 0.026$	2
R Tri	M4IIIe	266.40	51092	$3.570 \pm 0.091$	2
S Lac	M5e	239.67	51006	$2.862 \pm 0.107$	4
TU And	M5e	316.06	50855	$2.933 \pm 0.089$	5
U Cas	Sse	277.31	50680	$1.859 \pm 0.343$	7
R Gem	Se	369.63	50380	$2.886 \pm 0.194$	5
V Cmi	M6.5e	366.10	50817	$2.751 \pm 0.119$	2
R Psc	M4e	344.04	50763	$3.156 \pm 0.163$	7

## 3. Pulsation Modes

A considerable volume of literature exists concerning the debate about the pulsational mode of mira variables. Classical methods (before optical and near-IR interferometers became widely used) compared the predictions of theory and observations of miras, depending mainly upon estimates of temperature and luminosity to determine physical characteristics of these stars. When Glass & Lloyd Evans were able to demonstrate that mira variables in the Large Magellanic Cloud (LMC) fit a period-bolometric magnitude relation (1981) it became possible to more reliably estimate distances to these stars. However, it was not until the Hipparcos mission that any but the very closest miras could have reliable distance estimates. Now, with the large variety of spatial scales surveyed by modern optical and near-IR ground-based interferometers, and parallax data from missions such as Hipparcos, it may be possible to answer the question of pulsation mode for mira variables unambiguously.

Mira variables are, to first order, radial pulsators whose pulsation is driven mainly by hydrogen ionization effects. The basic question at hand is to know which mode, the fundamental or first-overtone, is the primary mode of pulsation. Pulsation arises as a consequence of an instability between gravitational restoring forces and thermodynamic pressure forces created by hydrogen ionization turning on in the shell-burning layers when the star heats up rapidly under contraction. Physically, a star with a large central mass concentration is more "tightly bound" than one with a smaller central mass and is expected to pulsate at a higher frequency.

We have taken distance estimates from three sources to apply to the problem of determining the physical size and thus likely pulsation mode for these miras. The first source is the Hipparcos database, for which there are published error estimates. Many of the stars in this sample must be far away in order to be resolved within the first null of PTI, thus they are not well-placed for measurements with Hipparcos. The second source is van Leeuwen et al. (1997) where they have calibrated the zero-point of the  $M_K$ -P relation for Galactic oxygen-rich Miras by using Hipparcos parallaxes and adopting the slope obtained for the LMC to obtain the relation:

$$M_K = 0.94 - 3.47 \log P \quad (2)$$

where  $M_K$  is the absolute bolometric magnitude of the mira at K band, and P is the period in days. To use this equation, we obtained archival K band magnitudes or fluxes from the Catalog of Infrared Observations for the stars in our sample. Because mira variables vary less than about 1.0 magnitudes at K band with phase, we are not likely to make a large error by estimating distances from K-band magnitudes at unknown phases in this way. Our final source for distance determination was from Alvarez & Mennessier (1997) where they determined the effective temperatures for 165 oxygen-rich miras using indices related to molecular band strength of TiO and VO computed from narrow-band photometric observations to obtain a period-luminosity relation and distances for these stars. Because no error estimates are presented with the van Leeuwen et al. or Alvarez & Mennessier data, error bars of 15% are assumed. See Table 2 for the distances.

From these distance estimates and our angular diameters, it is straightforward to estimate the physical sizes of the miras. We plot these radii (in units of  $R_{\odot}$ ) versus log of the period and superimposing models for the fundamental pulsation solution from Wood (1990):

$$\log P = 1.949 \log R - 0.9 \log M - 2.07 \quad (3)$$

where M is the mass in solar units, R is the radius in solar units and P is the period in days. For the first overtone, we use the standard relation:

$$\log P = 1.5 \log R - 0.5 \log M + \log Q \quad (4)$$

where all constants have the same meaning and  $Q = 0.04$  (similar to the values predicted by Fox & Wood, 1982). See Figure 4 for the plots. We conclude, based on this small sample of stars, that these oxygen-rich miras are likely pulsating in the fundamental mode.

These results, while not in agreement with those of van Leeuwen et al. (1997) for a sample of miras measured by Hipparcos and with the COAST interferometer, are not necessarily surprising. While angular diameter measurements, taken in conjunction with period-luminosity relationships, tend to favor first-overtone pulsation (c. f. Feast 1996), the excitation mechanisms necessary to produce observed spectral lines are only produced in fundamental mode pulsators (c. f. Bessell, Scholz & Wood 1996). It is unlikely that our assumption of a uniform disk would change these results, as it is estimated that limb-darkened disk values are only a factor of 1.02 greater than uniform disk models for normal late-type stars (Ridgway et al. 1980).

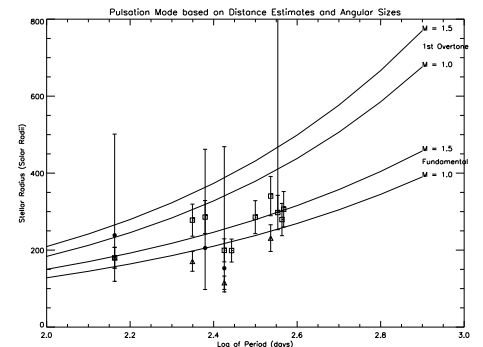


Fig. 4 We plot estimated radius (in solar radii) of the ten miras in this sample versus log of the period based on the different distance estimates described in the text. (Circles = Hipparcos, Triangles = Alvarez & Mennessier, Squares = van Leeuwen) The error bars are those quoted by Hipparcos for that dataset, and assumed to be 15% for the other two data sets. The lines shown are models for fundamental and first overtone pulsation for 1.0 and 1.5  $M_{\odot}$  stars. (See text for details.)

## 4. Conclusions and Future Work

We have demonstrated both phase dependent size variations (on the order of 17%) and plausible pulsation in the fundamental mode for a sample of ten mira variables with the Palomar Testbed Interferometer. These observations demonstrate the power of a tool such as an optical/near-IR interferometer in answering fundamental questions in stellar astrophysics.

We intend to continue this work during the 2000 observing season, attempting to obtain more phase coverage on a larger sample of stars to build a database of statistics on the pulsational characteristics of this sample. Further related work on the spectral changes with phase are being conducted by Thompson et al. (this conference) to ascertain the part acoustic shocks play in the atmospheric changes in these star systems.

We would like to acknowledge the assistance of several members of the PTI collaboration in the preparation of this manuscript. Special thanks to A. F. Boden for making numerous calibration and reduction scripts available to the collaboration. We would also like to thank R. P. Linfield, R. L. Akeson and C. D. Koresko for valuable assistance and conversations in regard to this data. M. C.-E. wishes to thank the NASA Origins Program for monetary assistance in support of her work with PTI.

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